Implications of the dimuon asymmetry in $B_{d,s}$ decay

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Outline

♦ Briefly: theory same sign lepton CP violation (CPV).

♦ General interpretation + linkage (?) with CPV in $B_{s,d}$ mixing

$\Rightarrow$ model indep’ interpretation.
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♦ Briefly: theory same sign lepton CP violation (CPV).

♦ General interpretation + linkage (?) with CPV in $B_{s,d}$ mixing => model indep’ interpretation.

♦ Minimalism: MFV explanation & GMFV (general minimal flavor violation).

♦ New realization: ultra-natural warped model & flavor triviality.

♦ Summary.
Effective $H$ for $B_q, \bar{B}_q$: $\mathcal{H} = M + i\Gamma/2$;

Mass eigenstates: $|B_{L,H}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle$.

Hence: 
\[
\alpha_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4}
\]

\[
\alpha_{SL}^b \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}}
\]
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$$a_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4} \left( a_{SL}^b \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}} \right)$$

$$M_{12} = |M_{12}|e^{i\phi_M}, \quad \Gamma_{12} = |\Gamma_{12}|e^{i\phi_{\Gamma}}. \quad \Rightarrow \quad a_{SL} = -\left|\frac{\Gamma_{12}}{M_{12}}\right| \sin(\phi_M - \phi_{\Gamma}).$$

$|\Gamma_{12}/M_{12}| \ll 1$ (valid for $B$ and $B_s$ mesons)
Effective \( H \) for \( B_q, \bar{B}_q \): \( \mathcal{H} = M + i \Gamma / 2 \);

\begin{itemize}
  \item Mass eigenstates: \(|B_{L,H}\rangle = p|B_q\rangle + q|\bar{B}_q\rangle\).
\end{itemize}

Hence:

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\alpha_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4} \quad \left( a_{SL}^b \equiv \frac{N_{b++} - N_{b--}}{N_{b++} + N_{b--}} \right)
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\]

\[
|\Gamma_{12}/M_{12}| \ll 1 \quad \text{(valid for } B \text{ and } B_s \text{ mesons)}
\]

\begin{itemize}
  \item SM (GIM): \( a_{SL}^{d,s} \sim \frac{m_c^2}{m_W^2} \text{Im} \left( \frac{V_{cb}V_{cd,s}^{*}}{V_{tb}V_{td,s}^{*}} \right) = \mathcal{O} \left( 10^{-2}, -4 \right) \)
\end{itemize}
DØ reports 3.2σ in dimuon asymmetry; CDF improves ΔΓ_{s} vs. S_{ψφ} ??

**D0 result:**  
\[ a_{SL}^{b} \equiv \frac{N_{b}^{++} - N_{b}^{--}}{N_{b}^{++} + N_{b}^{--}} = -(9.57 \pm 2.51 \pm 1.46) \times 10^{-3} \]

\text{1005.2757.}

fragmentation correlates  
B_{d} \leftrightarrow B_{s}

\[ a_{SL}^{b} = (0.506 \pm 0.043) a_{SL}^{d} + (0.494 \pm 0.043) a_{SL}^{s} . \]

Grossman, Nir & Raz, PRL (06).

**Data favors NP in B_{s} :**  
\[ (a_{SL}^{d})_{\text{exp}} \ll a_{SL}^{b} \Rightarrow a_{SL}^{s} \sim a_{SL}^{b} \]

**Requires large new phase,**  
\[ a_{SL}^{s} = - \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin(\phi_{M} - \phi_{R}). \]
DØ reports $3.2\sigma$ in dimuon asymmetry; CDF improves $\Delta \Gamma_s$ vs. $S_{\psi\phi}$ ??

♦ Origin of phase? $\Delta \Gamma_s^{NP} \iff$ overcome SM tree level and not violate other CPV, ex.: $b \to s\tau^+\tau^-$.  

Dighe, Kundu & Nandi [0705.4547, 1005.4051]  
Bauer & Dunn [1006.1629]

♦ Assuming no direct CP $\iff$ NP contributes to SM suppressed amplitudes $\Rightarrow$ correlation \w other observables:
DØ reports 3.2σ in dimuon asymmetry; CDF improves $\Delta \Gamma_s$ vs. $S_{\psi \phi}$ ??

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$\Delta \Gamma_s^{\text{NP}} = \Delta \Gamma_s$ 

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◆ Assuming no direct CP ↔ NP contributes to SM suppressed amplitudes $\Rightarrow$ correlation \w other observables:

$$a_{SL}^s = -\frac{|\Delta \Gamma_s|}{\Delta m_s} S_{\psi \phi} / \sqrt{1 - S_{\psi \phi}^2}$$

Ligeti, Papucci & GP, PRL (06);  
Correlation with $\Delta \Gamma_s$ vs. $S_{\psi\phi}$

(more exciting results just after this talk)

♦ D0 result can be written as:

$$-|\Delta \Gamma_s| \simeq \Delta m_s (2.0 \, a_{SL}^b - 1.0 \, a_{SL}^d) \sqrt{1 - S_{\psi\phi}^2 / S_{\psi\phi}}.$$  

Ligeti, Papucci, GP & Zupan [1006.0432].
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Ligeti, Papucci, GP & Zupan [1006.0432].

♦ **Tevatron experiments** also measure:

![Diagram of correlation between $\Delta \Gamma_s$ and $S_{\psi\phi}$]

**New CDF measurement of $\beta_s$**

![CDF measurement of $\beta_s$ and $\Delta \Gamma_s$]

**CDF Public Note 9787**

Tevatron combination: probability of observed deviation from SM = 3.4% (2.12 $\sigma$)

P-value for SM point: 44% (0.8$\sigma$ deviation)
Correlation with $\Delta \Gamma_s$ vs. $S_{\psi\phi}$

(more exciting results just after this talk)

- **D0** result can be written as:

  $$-|\Delta \Gamma_s| \simeq \Delta m_s \left( 2.0 a_{SL}^b - 1.0 a_{SL}^d \right) \sqrt{1 - S_{\psi\phi}^2 / S_{\psi\phi}}.$$

- **Tevatron experiments** also measure:

  ![Diagrams showing correlation between $\Delta \Gamma_s$ and $S_{\psi\phi}$ and measurements from D0 and Tevatron experiments.](image)

  **Tevatron combination**: probability of observed deviation from SM = 3.4% (2.12 $\sigma$)

  CDF Public Note 9787

  Ligeti, Papucci, GP & Zupan [1006.0432].
Combining $a_{b_{SL}}^b$ & $\Delta \Gamma_s$ vs. $S_{\psi\phi}$

- **Consistency check:**

\[
(a_{SL}^b)_{D\Ø} : \quad |\Delta \Gamma_s| \sim (0.28 \pm 0.15) \sqrt{1 - S_{\psi\phi}/S_{\psi\phi}} \text{ ps}^{-1}
\]

\[
(S_{\psi\phi})_{CDF+D\Ø} : \quad (\Delta \Gamma_s, S_{\psi\phi}) \sim (0.15 \text{ ps}^{-1}, 0.5)
\]

- **Can use data to fit $\Delta \Gamma_s$ => no theory involved.**

Ligeti, Papucci, GP, Zupan.
Model independent interpretation
Global NP fit

Clean NP interpretation: $M_{12}^{d,s} = (M_{12}^{d,s})^{\text{SM}} (1 + h_{d,s} e^{2i\sigma_{d,s}})$.

$(\Delta \Gamma_s$ is taken from the fit $\rightarrow$ not theory involved)

$h_i$: magnitude of NP normalized to SM.

$\sigma_i$: NP relative phase.

$$\Delta m_q = \Delta m_q^{\text{SM}} |1 + h_q e^{2i\sigma_q}|,$$

$$\Delta \Gamma_s = \Delta \Gamma_s^{\text{SM}} \cos \left[ \arg (1 + h_s e^{2i\sigma_s}) \right],$$

$$A_{SL}^q = \text{Im} \left\{ \frac{\Gamma_{12}^q}{M_{12}^{q,\text{SM}} (1 + h_q e^{2i\sigma_q})} \right\},$$

$$S_{\psi K} = \sin \left[ 2\beta + \arg (1 + h_d e^{2i\sigma_d}) \right],$$

$$S_{\psi\phi} = \sin \left[ 2\beta_s - \arg (1 + h_s e^{2i\sigma_s}) \right].$$
Global fit’s results

$B_d$ vs. $B_d$ systems

(we used CKMfitter)
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$B_d$ vs. $B_d$ systems

(we used CKMfitter)

Data favors $h_s > h_d$
Allowed regions in the $B_s$ & $B_d$ systems.

The allowed ranges of $h_s, \sigma_s$ (left) and $h_d, \sigma_d$ (right) from the combined fit to all four NP parameters.
Universal case: \( h_d = h_s, \quad \sigma_d = \sigma_s \)

Viable with some tension.

The allowed \( h_b, \sigma_b \) range assuming \( SU(2) \) universality.
Lessons from the data, model indep’

- Tension with SM null prediction.
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- SU(2)_q approx’ universality, \( h_s \sim h_d \), can accommodate data; arise in many models with NP effects via 3rd gen’.
Lessons from the data, model indep’

♦ Tension with SM null prediction.

♦ SU(2)_q approx’ universality, h_s \sim h_d , can accommodate data; arise in many models with NP effects via 3rd gen’.

♦ However, data favors h_s \gg h_d , seems more challenging. (most theoretical explanation involved tuning of parameters)
Some Model Dependent Implications

GMFV: (i) EFT (ii) Higgs exchange (iii) warped Xtra dim’
GMFV (general minimal flavor violation): simple framework that account for data

- MFV (@ TeV) + flavor diag’ phases $\Rightarrow O(1)$ CPV in $b \rightarrow d,s$.
  Colangelo, et al. (09); Kagan, et al. (09).

- MFV is a natural limit of many theories & by analyzing the data within MFV we learn about the necessary NP structure that can explain it.

- Surprisingly it can accommodate both above cases:
  \[(1) \ h_s \sim h_d \ , \ (2) \ h_s \gg h_d \ . \]
GMFV: Linear MFV vs Non-LMFV & CPV

Kagan, GP, Volansky & Zupan (09); 2 x Gedalia, Mannelli & GP (10).
What defines MFV Pheno’?

◆ Is CPV is broken only by the Yukawa or flavor diag’ phase are present?

◆ Is the down type flavor group is broken “strongly”?

◆ Is the up type flavor group is broken “strongly”?
The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively.

“LO” MFV expansion valid only for

\[ \bar{Q} f(\epsilon_u Y_U, \epsilon_d Y_D) Q \]
\[ \epsilon_u, \epsilon_d \ll 1 \]

Large "logs" or anomalous dim’ => \( \epsilon_{u,d} = \mathcal{O}(1) \)
The top Yukawa is large (possibly also bottom one) no justification to treat it perturbatively.

“LO” MFV expansion valid only for \[ Qf(\epsilon_uY_U, \epsilon_dY_D)Q \]
\[ \epsilon_u, \epsilon_d \ll 1 \]

Large ”logs” or anomalous dim’ \[ \Rightarrow \epsilon_u, \epsilon_d = \mathcal{O}(1) \]

We distinguish between 2 cases LMFV & NLMFV:

- **Linear MFV (LMFV):** \( \epsilon_u, \epsilon_d \ll 1 \) and the dominant flavor breaking effects are captured by the lowest order polynomials of \( Y_u, Y_d \).

- **Non-linear MFV (NLMFV):** \( \epsilon_u, \epsilon_d \sim O(1) \), higher powers of \( Y_u, Y_d \) are important, and a truncated expansion in \( y_{t,b} \) is not possible.
What defines MFV Pheno’?

♦ If flavor diag’ phase are present then one can get large b→d,s CPV with: \((B_s)_{\text{CPV}} \geq (B_d)_{\text{CPV}}\) or \(h_s \geq h_d\)


♦ Only if down type flavor group is broken “strongly” then we can expect \((B_s)_{\text{CPV}} > (B_d)_{\text{CPV}}\) or \(h_s > h_d\)

Since new non-universal CPV \(\propto [Y_uY_u^\dagger, Y_dY_d^\dagger]\)

Gedalia, Mannelli & GP (10); Blum, Hochberg & Nir (10).
MFV, effective operators

♦ Universal solution: \((h_s \sim h_d)\)

\[ \Lambda_{\text{MFV};1,2,3} \gtrsim \{8.8, \; 13 \, y_b, \; 6.8 \, y_b\} \sqrt{0.2/h_b} \; \text{TeV}. \]

\[ O_1^{bq} = \bar{b}_L^\alpha \gamma_\mu q_L^\alpha \bar{b}_L^\beta \gamma_\mu q_L^\beta, \; O_2^{bq} = \bar{b}_R^\alpha q_L^\alpha \bar{b}_R^\beta q_L^\beta, \]

♦ Non-univ. solution: \((h_s \gg h_d)\)

\[ O_4^{\text{NL}} = \frac{c}{\Lambda_{\text{MFV};4}^2} \left[ \bar{Q}_3 (A_d^m A_u^n Y_d)_{3i} d_i \right] \left[ \bar{d}_3 (Y_d^l A_d^{l,\dagger} A_u^{p,\dagger})_{3i} Q_i \right]. \]

\[ \Lambda_{\text{MFV};4} \gtrsim 13.2 \, y_b \, \sqrt{m_s/m_b} \; \text{TeV} = 2.9 \, y_b \; \text{TeV}. \]
Scalar exchange

Buras, et al. (10); Dobrescu, et al. (10); Jung, et al. (10); Nir et al. (10).

- 2HDM a natural arena to generate flavor & CPV within MFV.

- Universal solution can easily be generated via $O_2$

- Non-univ. solution only if $O_4 \gg O_2$
Vector exchange (KK gluon)

- Radical solution to little RS CP problem via bulk realization of Rattazzi & Zaffaroni’s flavor model.

- New type of GMFV models with large LL and/or RR currents.

- Low KK scale + improve naturalness as a bonos => exciting LHC phenomenology => linkage between high & low pT data!
Data seem to suggest for new source of CPV.

Consistent NP interpretation favoring large $B_s$ contributions; if no direct CP (width diff’ => from data) clean theoretically.

Can be accounted for by MFV (including $B_s > B_d$).

Possible linkage to NP scalar GMFV physics (UV physics fuzzy).

Ultra natural warped models => GMFV => can explain the data via KK gluon exchange, via LLRR operators.

Low KK scale => soon tested @ LHC+flavor gauge bosons.